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REPORT OF INVESTIGATIONS/1991

Improved Drilling of Coal Measure Rocks for Underground Mine Void Detection and Exploration Programs

By Pamela J. Watson, Patrick A. Tuzinski, and John E. Pahlman

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	L	liter
ft/min	foot per minute	mg/L	milligram per liter
g	gram	min	minute
gal	gallon	mL	milliliter
g/L	gram per liter	pct	percent
gpm	gallon per minute	ppm	part per million
h	hour	rpm	revolution per minute
in	inch		

IMPROVED DRILLING OF COAL MEASURE ROCKS FOR UNDERGROUND MINE VOID DETECTION AND EXPLORATION PROGRAMS

By Pamela J. Watson,[1] Patrick A. Tuzinski,[2] and John E. Pahlman[3]

ABSTRACT

The U.S. Bureau of Mines has demonstrated in laboratory tests that drilling with surface-charge-neutralizing concentrations of polyethylene oxide (PEO) polymer solutions simultaneously improves penetration rates and extends bit life. The applicability of this additive to improve drilling performance in coal measure rocks was demonstrated under field conditions at an abandoned mine land site in Pennsylvania and a producing coal mine property in Ohio. Penetration rate improvements ranging from 15 to 50 pct were obtained when core drilling through a variety of coal measure lithologies. Drilling cost analysis indicates that the small added cost of using the polymer is more than offset by the savings that result from demonstrated increased drilling penetration rates, which translate into drilling cost savings of about 10 to 30 pct.

This report also gives chemical analyses of a variety of coal measure rocks and some corresponding local drilling water samples, obtained from a wide geographical base, along with threshold concentrations of PEO required to effect the improved drilling performance in these rocks. From these data, the threshold PEO concentrations needed to ensure improved drilling performance can be estimated for any coal measure rock suite. Proper techniques for mixing PEO solutions are also presented.

[1]Mining engineer.
[2]Research geochemist.
[3]Supervisory physical scientist.
Twin Cities Research Center, U.S. Bureau of Mines, Minneapolis, MN.

INTRODUCTION

UNDERGROUND VOID DETECTION OF ABANDONED MINE LANDS

Stabilization of abandoned mined lands has become a necessary and significant activity in the Eastern, Interior, and Western coal provinces in the United States. Abandoned mines have the potential of presenting some serious obstacles to current and future use of the lands. Underground voids created by old mine workings pose imminent problems to the potential surface users of the land, from the aspects of both drainage and surface structural damage. Failure of these underground voids can create topographic changes characterized by tilt, curvature, and displacement of the ground surface. Failure can also alter hydrological patterns and, in areas of shallow water tables, even cause minor ground depressions and ponding of water. In rural areas, subsidence can cause breaking of tile drainage lines and/or disruption of surface drainage ditches and natural drainage channels. In urban areas, subsidence can cause water and natural gas pipes to leak or rupture, roads to buckle, and foundations to crack or even crumble. An additional concern is the potential for injury or loss of life to humans and animals in subsidence-prone areas.

Stabilization of undermined areas requires cost-effective techniques for detecting and delineating the extent of old mine voids. Such delineation is simple and cost effective if mine maps are available and are accurate. In the majority of cases, however, maps are not available or are inaccurate; therefore, voids have to be detected and delineated by some other method. Geophysical methods have been investigated, but to date, they have not been entirely successful in defining the extent of underground voids with the required level of accuracy. In addition, many noninvasive techniques are expensive. Drilling is currently the most successful method to define and delineate the extent of underground voids and, in some cases, is the only practical choice. However, it is also expensive and can quickly consume the total budget for a given abandoned mine land (AML) reclamation project. Low penetration rates coupled with short bit life and the frequent downtime associated with changing of the worn bits are counterproductive and increase overall drilling costs.

The U.S. Bureau of Mines research described in this report is part of an ongoing project to evaluate the effectiveness of polyethylene oxide (PEO) in enhancing drilling performance. This phase of the project was undertaken to demonstrate the use of PEO solutions as drilling fluids to improve drilling performance in coal measure rocks. Improved performance, including increased bit life and increased penetration rates, makes drilling a more cost-effective tool for detection and delineation of underground mine voids. This work is part of the Bureau's program to develop technology that can help minimize the environmental impacts of past mining operations.

NEUTRALIZATION OF ROCK SURFACE CHARGE

Previous research on the use of chemical additives to improve drilling performance has shown that drilling performance is substantially enhanced when the surface charge (the zeta potential) of the rock is neutralized. In typical mine drilling waters with pH in the range of 6 to 8, most rocks exhibit a negative surface charge. One method of neutralizing the rock surface charge is to use cationic chemical additives such as inorganic salts, cationic organic surfactants, or cationic polymers. The use of cationic chemical additives to improve penetration while simultaneously extending bit life has been demonstrated in the laboratory for hard rocks such as Sioux Quartzite, Westerly Granite, and Minnesota taconite (*1-2*).[4] One drawback with using cationic additives is that there is only one concentration at which the rock surface charge is neutralized. Addition of more of the cationic additive results in a positive surface charge and a loss of the improved drilling performance.

More recently, it has been found that PEO, a water-soluble, nonionic polymer, has the ability to hydrogen bond with water molecules to produce positive dipoles capable of neutralizing the negative rock surface charge. The difference between PEO and the cationic additives is that since the PEO polymer molecule is nonionic or neutral, addition of more PEO beyond the initial neutralizing or threshold concentration will not cause the rock surface charge to become positive; instead, the surface charge remains zero or neutral. Thus, the PEO concentration in the drilling fluid can be at or above the threshold concentration to ensure the enhanced drilling performance. Laboratory drilling tests with PEO (*2-3*) have produced increases of 350 and 650 pct in total penetration and simultaneous increases of 230 and 400 pct in bit life when drilling Sioux Quartzite and Minnesota taconite, respectively. A field test of the PEO in diamond drilling of

[4]Italic numbers in parentheses refer of items in the list of references preceding the appendix at the end of this report.

granite at Sudbury, Ontario, Canada, resulted in an almost threefold increase in bit life. Furthermore, a 72-pct increase in penetration rate (0.93 ft/min versus 0.56 ft/min) and a 26-pct increase in bit life (3,400 ft versus 2,700 ft) were realized during drilling of Minnesota taconite with 15-in-diameter rotary tricone bits using an air-polymer solution mist for flushing of drilling particulates. As an example of the cost savings that can be realized by using this polymer, the 26-pct bit life increase would result in a cost savings of approximately $95,000 per year per drill, based on the company's yearly average number of bits used at a cost of $5,500 each. Similar increases in drilling penetration and bit life when drilling to detect and delineate underground voids in abandoned mine lands could result in substantial savings to the AML program. This research was conducted to test the use of PEO in the rock suites normally encountered in coal mining areas and thus would have application in coal exploration drilling in addition to underground mine void detection and delineation.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Douglas L. Crowell, geologist and drilling program coordinator, Ohio Department of Natural Resources, for arranging contacts with the Central Ohio Coal Co. (COCC), where the Ohio field tests took place; to Thomas Swinehart, manager of exploration, COCC, for arranging the cooperative agreement; to COCC site geologist, Phil Forshey, and drillers, Dennis Bickford and Terry French, who were invaluable in the successful planning and completion of the cooperative drilling tests; and to Keith Davis, contract manager for American Electric Power Service Corp. (COCC's parent organization), who arranged the proper service contract between the Bureau and his company, which allowed the cooperative drilling test to proceed.

The authors would also like to express their appreciation to Steve R. Jones, chief, Mine Fire and Mine Subsidence Control Section, Division of Mine Hazards, and Tim Altares and Veronica Kasey, project geologists, all with the Pennsylvania Department of Environmental Resources, Bureau of Abandoned Mine Land Reclamation, for arranging and conducting the field test of PEO in Pennsylvania.

DESCRIPTION OF PEO

The chemical additive used in the drilling tests, polyethylene oxide (PEO), is a high-molecular-weight, long-molecular-chained, nonionic polymer, available as a white powder. It is nontoxic and safe with respect to both the environment and the health and well-being of mine personnel. The U.S. Environmental Protection Agency has given approval for a wide variety of applications of PEO in solution, including agricultural uses in seed coatings, in crop sprays, and as a soil stabilizer. In addition to being nonhazardous to the environment, PEO breaks down in nature to other inert substances over a time span of a few months and evaporates, leaving little or no residue. The U.S. Food and Drug Administration has also given wide approval for the commercial uses of PEO, including use as an ingredient in denture adhesives, cosmetics, soaps, and detergents, use as a coating of or ingredient in pharmaceutical tablets, and use as a foam stabilizer for beer.

As described in this report, PEO may also be used as an additive in drilling fluids to reduce bit wear and improve drilling ease. Proper mixing of PEO with water is essential to the successful preparation of PEO drilling fluids. Additional information about PEO and specific and detailed instructions on proper mixing techniques are included in the appendix of this report.

DETERMINING THRESHOLD PEO CONCENTRATIONS FOR COAL MEASURE ROCKS

Samples of representative coal measure rocks (including limestones, sandstones, shales, basalts, siltstones, claystones, mudstones, and coals) were obtained by the Bureau from State AML agencies and cooperating mine owners in Alabama, Colorado, Illinois, Kentucky, Montana, Ohio, Pennsylvania, and West Virginia. In addition, some corresponding local drilling water samples were obtained. The quality of the local drilling water is an essential factor in determining the proper concentration of PEO additive needed to neutralize the surface charge of a given rock.

Zeta potential measurements were performed on all rock samples received, in the corresponding local drilling water (when available) and in Minneapolis tap water for baseline comparisons. Zeta potentials provide a measure of the rock surface charge and are negative, zero, or positive depending upon whether the rock surface charge is negative, neutralized, or positive. The zeta potential measurement techniques are described elsewhere (*4*). The threshold PEO concentration is the minimum concentration at which the zeta potential becomes zero. The ranges of the threshold PEO concentrations for all rock types tested are listed in table 1. No rock tested required more than 15 ppm of PEO, with most requiring only 7.5 ppm. Specific threshold PEO concentrations are listed in table A-1 of the appendix for the coal measure rock samples, in both Minneapolis tap water and, when applicable, local drilling waters.

Table 1.—Ranges of threshold PEO concentrations

Lithology	Number of samples tested	PEO required, ppm
Coal	17	7.5-10.0
Basalt	2	7.5
Claystone	17	7.5-15.0
Conglomerate	3	7.5
Greywacke	1	7.5
Limestone	32	5.0-10.0
Mudstone	5	5.0-10.0
Sandstone	48	5.0-10.0
Shale	63	5.0-10.0
Siltstone	12	7.5-10.0
Slate	1	7.5

Chemical analyses of the corresponding local drilling waters and the coal measure rock samples are listed in appendix tables A-2 through A-9. Chemical analyses were conducted to define the range of chemical compositions for typical coal measure rocks, as well as the range of chemical compositions of drilling water. These data should assist in determining how differences in composition affect the threshold PEO concentration. Thus, the tables in the appendix may be used to determine the threshold PEO concentration of any coal measure rock suite without the necessity of actually measuring zeta potential.

1. First, the chemical analyses for each coal measure rock type of a given mine or drilling operation are compared with those listed in appendix tables A-3 through A-9 to find a similar rock composition. An approximation can be made if actual whole-rock analyses are not available.

2. Next, the threshold PEO concentrations for each similar rock type composition are found by cross-referencing sample numbers in table A-1 (where samples are listed by State and location).

Determination of actual polymer concentration used in subsequent drilling would depend upon the closeness of the composition of the local drilling water to the composition of the water used in the zeta potential measurements and the variability in threshold PEO concentrations determined for each rock type in the given rock suite.

1. The first step consists of (1) comparison of the chemical analyses of the local drilling water with those for Minneapolis tap water and the various mine waters listed in table A-2, (2) determination of the difference in the PEO threshold concentrations for the similar-composition water in table A-2 and the baseline Minneapolis tap water by cross-referencing to table A-1, and (3) addition of that difference to the threshold PEO concentration determined previously by matching rock analyses.

2. The second step is the determination of the highest threshold PEO concentration for any rock type in the given rock suite; this is the minimum PEO concentration required for enhanced drilling performance of the coal measure rock suite.

For example, a driller is planning to drill through a sandstone with a composition very similar to that of Ohio sample 8444 (COCC, corehole JMB 26-20, 133.92 ft) as listed in table A-6. The water to be used is similar to Minneapolis tap water as listed in table A-2. Then, by referencing table A-1, the required concentration of PEO would be determined to be 5.0 ppm. This or a higher concentration would be used for the drilling fluid.

Based on the data in the appendix tables, it would appear that for the vast majority of cases the highest threshold PEO concentration for any rock type is 10 ppm or lower. Employing a safety factor of 5 ppm to cover losses due to drilling particulate flocculation if the water is recirculated, the PEO concentration for drilling of the vast majority of coal measure rock suites should be around 15 ppm or less. It should be noted, however, that the poorer the water quality, the more PEO will be needed to ensure neutralization of the rock surface charge.

FIELD DRILLING TESTS

A field drilling test was conducted with COCC as part of its current exploration drilling program at the Muskingum Mine near Cumberland, OH. Another field drilling test was conducted in Pennsylvania at the Rulli Mine AML site in Connellsville, PA.

OHIO

Drilling Test Program

The cooperative program to test PEO as a drilling fluid additive consisted of drilling 11 NQ-size (3-in) coreholes, ranging in depth from 55 ft to well over 150 ft. Six holes were drilled with water alone, while five holes were drilled with zero-surface-charge (ZSC) concentrations of 15-ppm PEO solutions. The 15-ppm PEO concentration was used because of the poor quality of the drilling water in the sump and to offset losses due to drilling particulate flocculation in the sump. The PEO drilling tests were conducted as follows: 20 gal of concentrated (4,500 ppm) PEO was initially added to the 6,000 gal of water introduced to the sump; water was then pumped from the sump to a 330-gal water trough in which the intake water hose for the drill was inserted; after augering had been completed, additional PEO concentrate (4,500 ppm) was dripped into the water trough from 5-gal containers at a rate that ensured that the concentration of the fluid pumped into the drill was at least 15 ppm. The water drilling tests were conducted without the water trough; water was pumped directly from the sump to the drill. In both PEO and water drilling tests, drilling fluid was returned to the sump from the drill hole for fluid recycling by means of a small ditch.

To aid in determining differences in drilling rates, a yardstick was mounted on the drill rig and marked off in 6-in segments with black tape. A stopwatch was started as the drilling began, and elapsed time was recorded as the drill head passed each 6-in interval on the yardstick. The stopwatch was stopped when drilling was stopped, i.e., at the end of a stroke, to pull core, to add on drill string, or at the end of the test. Drilling was done by COCC drillers with a Joy[5] RamRod 2 wire-line drilling rig. Bureau personnel were responsible for recording the times and depths, as well as mixing and adding the PEO as needed.

Field Drilling Results

Penetration rates (feet per minute) were determined for each 6-in interval. These values were then correlated with the lithologic logs of the coreholes obtained from COCC after the field work had been completed. The best basis of comparison for the drilling performance of PEO versus water was by penetration rate differences for the same stratigraphy or, in the case of entire holes, similar depths with similar stratigraphy. Figure 1 shows the spatial relationships of the 11 holes, JMB 26-20 through 26-22 and 35-16 through 35-23, drilled in the test program. (Hole identification numbers were assigned by COCC.) Although all the holes were relatively close together, only three pairs of holes could be compared because they were of comparable depth to coal and had similar stratigraphic intervals. Those sets of holes are enclosed in boxes in figure 1.

The final depth of the hole, the total time of drilling, the penetration rate, and the effect of PEO on drilling performance are summarized in table 2 and illustrated in figures 2, 3, and 4. As the data show, using PEO as the drilling medium improved penetration rates 39.4, 27.3, and 22.1 pct for the shallow, medium-deep, and deep holes, respectively. Comparisons among all these tests are illustrated in figure 5.

Table 2.—Field drilling test results, Ohio

Hole designation and drill medium	Depth of hole, ft	Time to drill, min	Overall penetration rate, ft/min	Penetration rate improvement with PEO, pct
Shallow:				
JMB 35-23 (water)	79.5	263.01	0.30	NAp
JMB 26-22 (PEO)	79.08	189.05	.42	39.4
Medium-deep:				
JMB 35-21 (water)	119.67	532.56	.22	NAp
JMB 35-22 (PEO)	109.67	395.18	.28	27.3
Deep:				
JMB 35-19 (water)	146.67	614.27	.24	NAp
JMB 35-20 (PEO)	166.67	568.91	.29	22.1

NAp Not applicable.

When similar lithologies were compared among these six holes, increased penetration rates were again obtained with PEO drilling solutions. Results of these comparisons are given in table 3 and illustrated in figure 6. These lithologies included shale above coal, all other shales, limestone, and claystone. With these lithologies, the use of PEO improved penetration rates more than 24 pct, with an improvement of almost 41 pct shown in drilling through claystone. Cost savings due to these increased penetration rates are summarized in the "Drilling Cost Analysis" section below.

Table 3.—Drilling results compared by lithologies, Ohio

Rock strata drilled	Penetration rate,[1] ft/min		Penetration rate improvement with PEO, pct
	With water	With PEO	
Shale above coal	0.18	0.23	27.8
All other shales	.21	.26	26.2
Limestone	.25	.31	24.0
Claystone	.18	.25	40.8

[1]Average of results for each lithology for the 6 holes that were compared.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

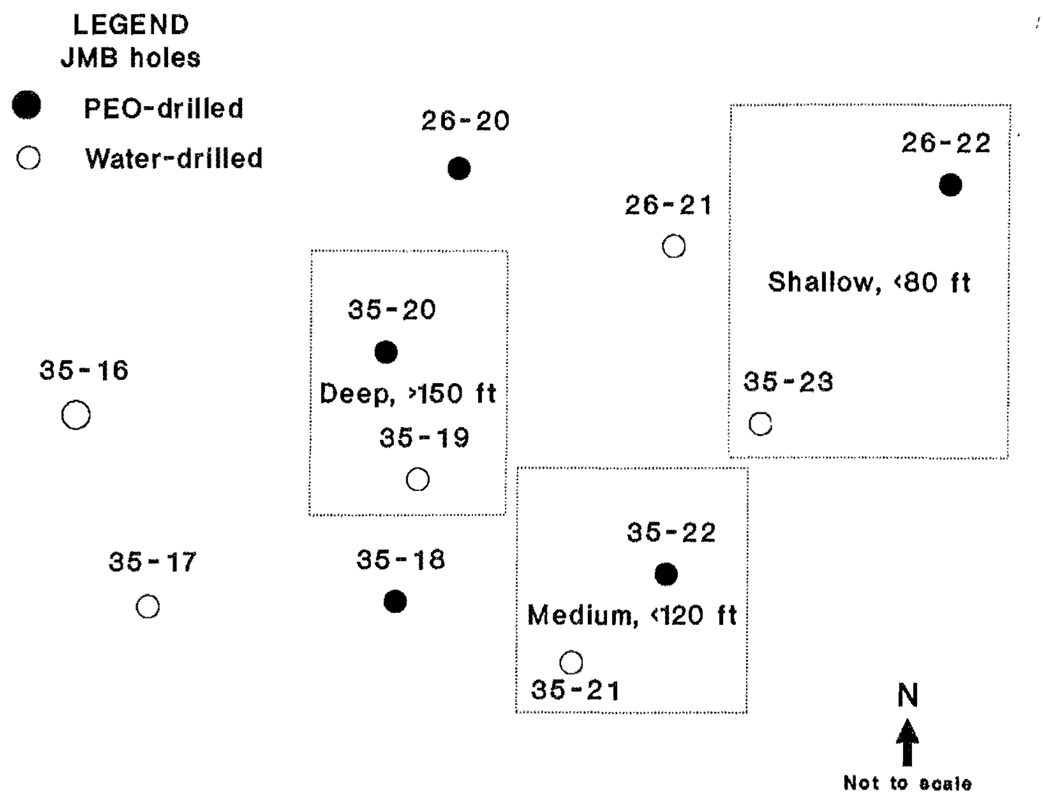

Figure 1.—Spatial relations of Ohio drill holes.

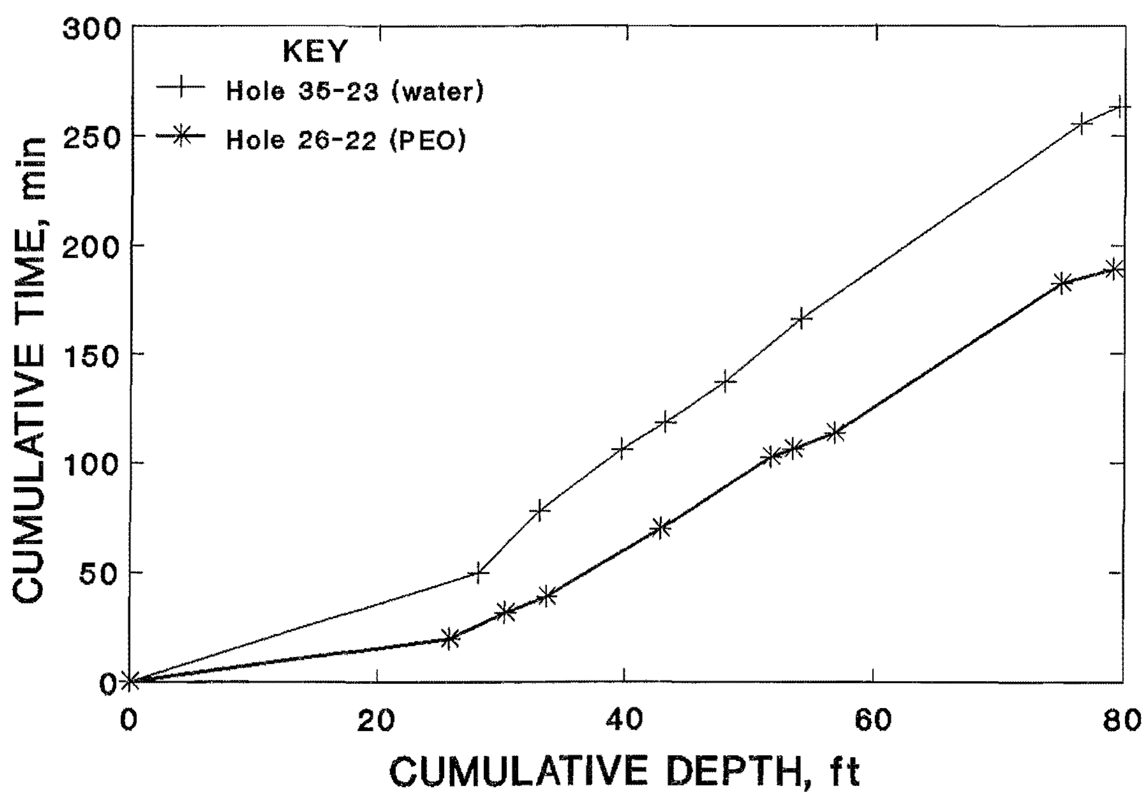

Figure 2.—Ohio drilling results comparing shallow holes.

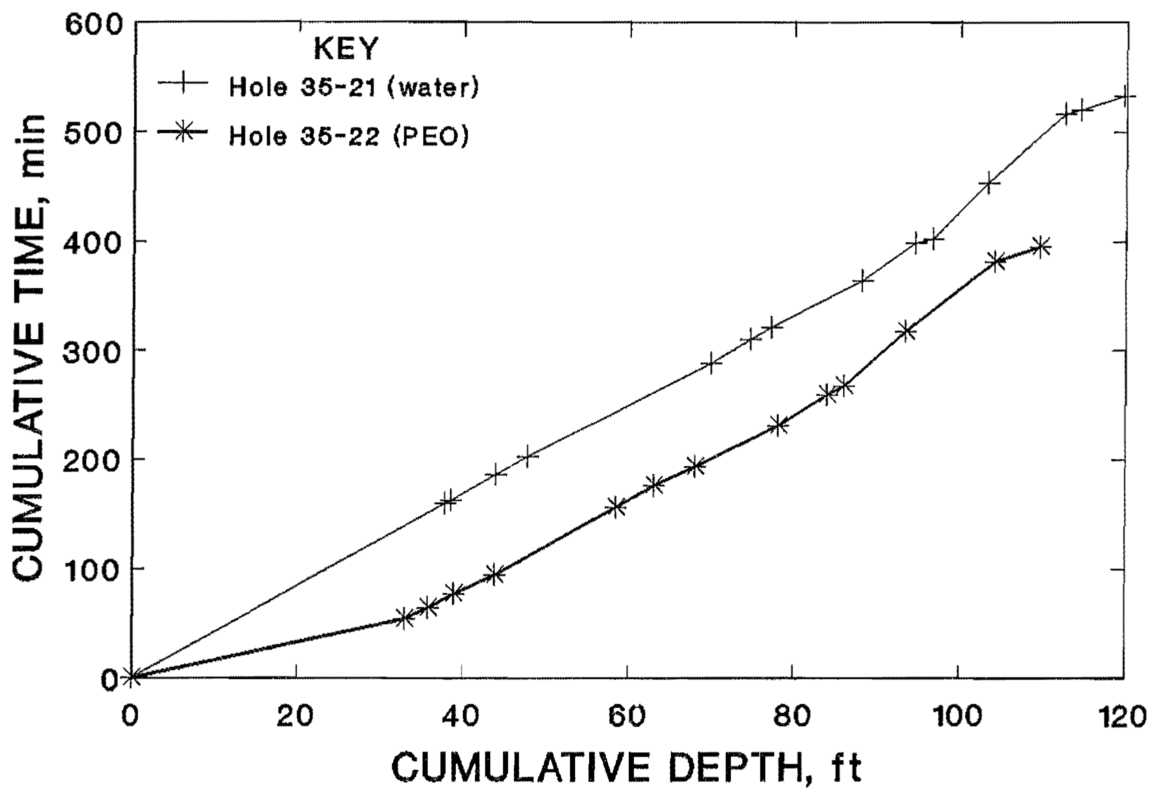

Figure 3.—Ohio drilling results comparing medium-deep holes.

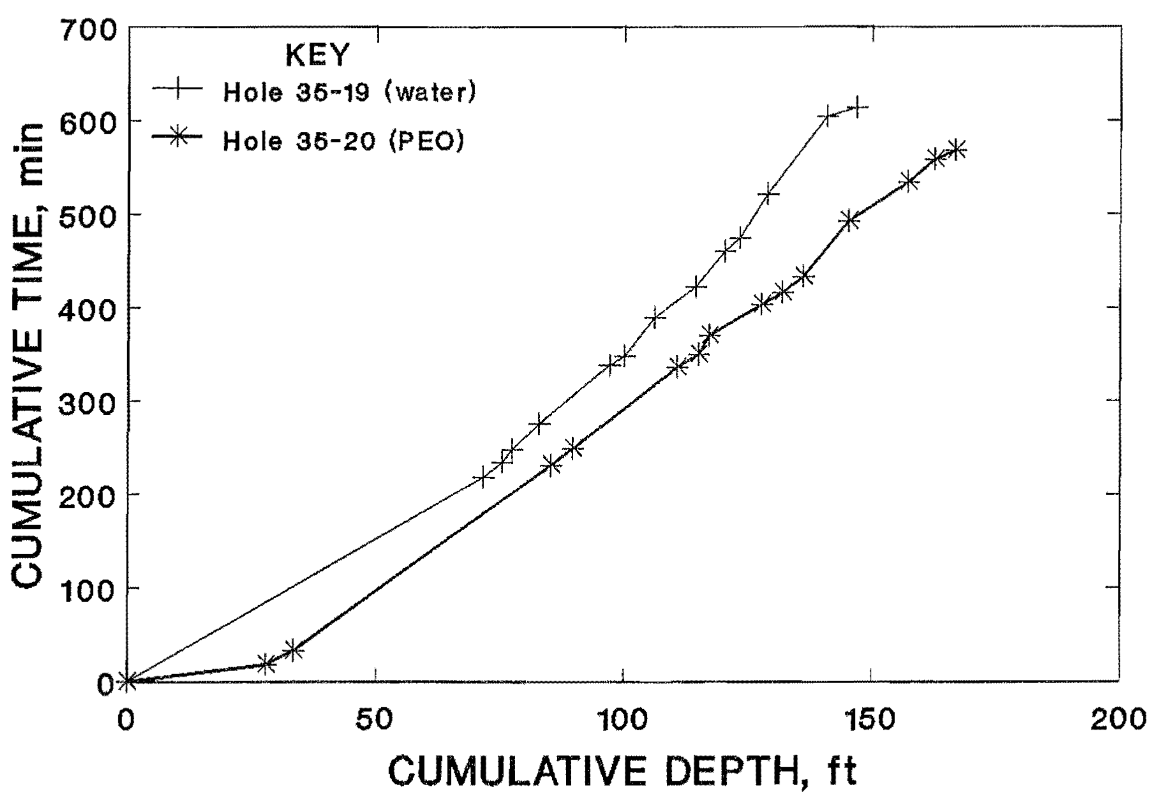

Figure 4.—Ohio drilling results comparing deep holes.

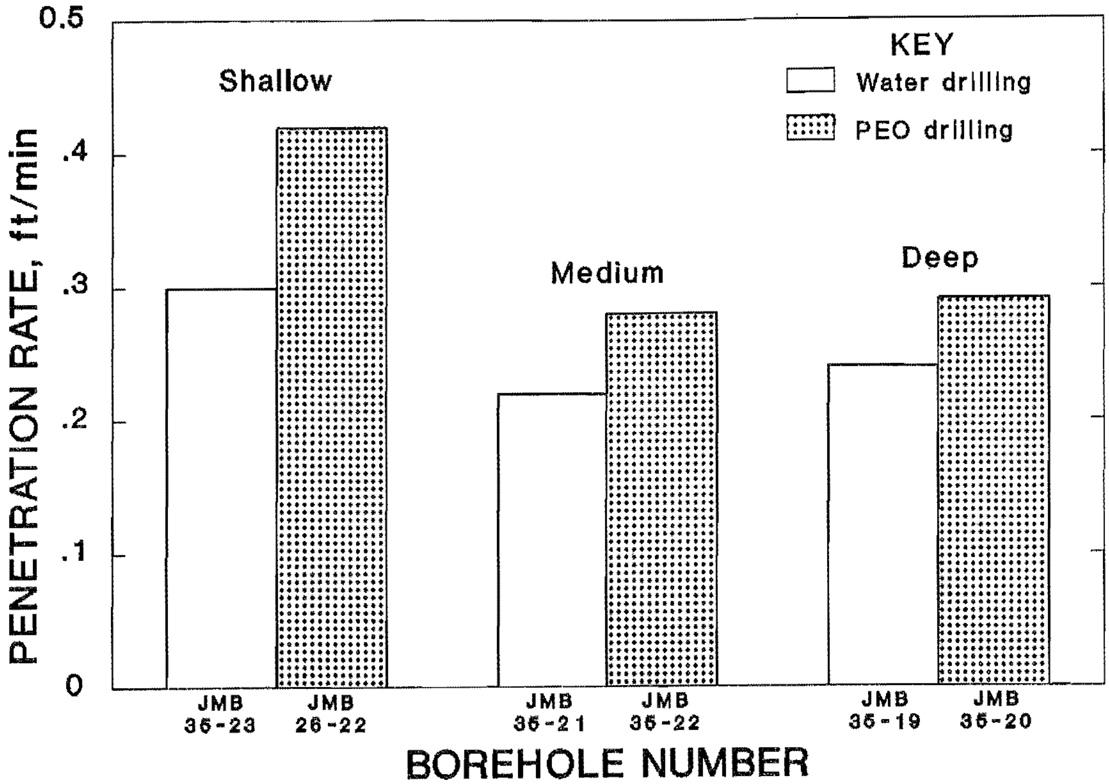

Figure 5.—PEO versus water drilling for Ohio holes.

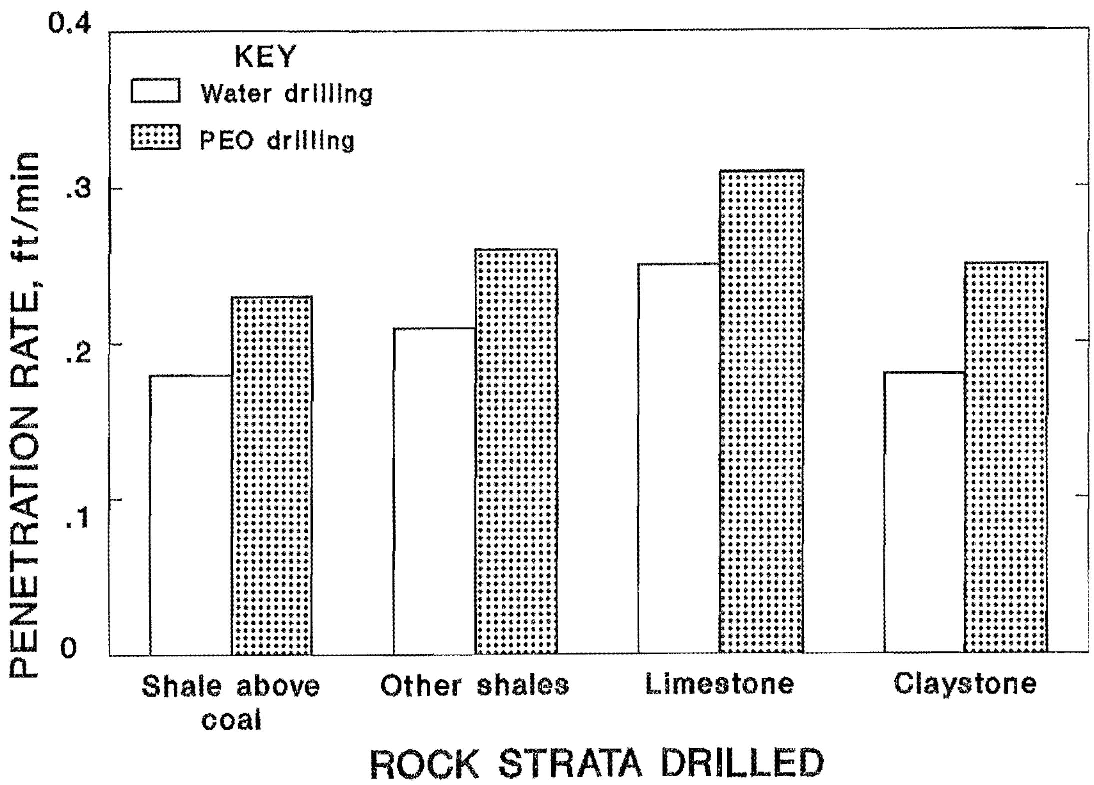

Figure 6.—PEO versus water drilling for specific Ohio rock lithologies.

PENNSYLVANIA

Drilling Test Program

Seventeen NQ-size (3-in) coreholes were drilled to depths ranging from 30 to 110 ft to determine the extent of an underground mine fire at the abandoned Rulli Mine. Of those 17 holes, 5 were drilled using 15-ppm concentration PEO solutions. Pennsylvania Department of Environmental Resources personnel and contract drillers conducted this drilling program with consultation from Bureau personnel. Figure 7 shows the locations of the 17 holes. Recording procedures were similar to those in the Ohio tests, with elapsed times being recorded every 6 in, or every foot, depending on the on-site geologist's discretion.

Field Drilling Results

Stratigraphic comparisons were made to determine which, if any, holes could be compared to ascertain the effect of PEO solutions in drilling. Because this test was conducted in a previously mined, significantly subsided area, correlation between holes was practically impossible. No two holes displayed similar lithologic intervals or thicknesses. Therefore, total-hole comparisons like those made in the Ohio tests were not practical. All of the holes, however, did contain similar rock lithologies between two coal layers, the Upper Pittsburgh rider and the main Pittsburgh Coal Seam. Therefore, comparisons were possible for four specific rock types lying between the coal layers: highly fractured claystone, fractured claystone, fractured claystone with interbedded layers of competent sandstone, and competent claystone. The results of the comparisons are summarized in table 4, and illustrated in figure 8. The PEO solutions improved the penetration rate in drilling each of the four lithologies. For drilling in highly fractured claystone, fractured claystone, fractured claystone with sandstone, and unfractured claystone with PEO solutions, the penetration rate improved 14.8, 35.1, 47.1, and 49.3 pct, respectively. An interesting fact is borne out by these data; i.e., drilling performance with PEO is enhanced for the more competent rocks.

Table 4.—Drilling results compared by lithologies, Pennsylvania

Rock strata drilled	Penetration rate,[1] ft/min		Penetration rate improvement with PEO, pct
	With water	With PEO	
Highly fractured claystone	0.54	0.62	14.8
Fractured claystone. .	.57	.77	35.1
Fractured claystone with interbedded sandstone	.70	1.03	47.1
Competent claystone	.71	1.06	49.3

[1]Average of results for each lithology for the holes having that rock strata present.

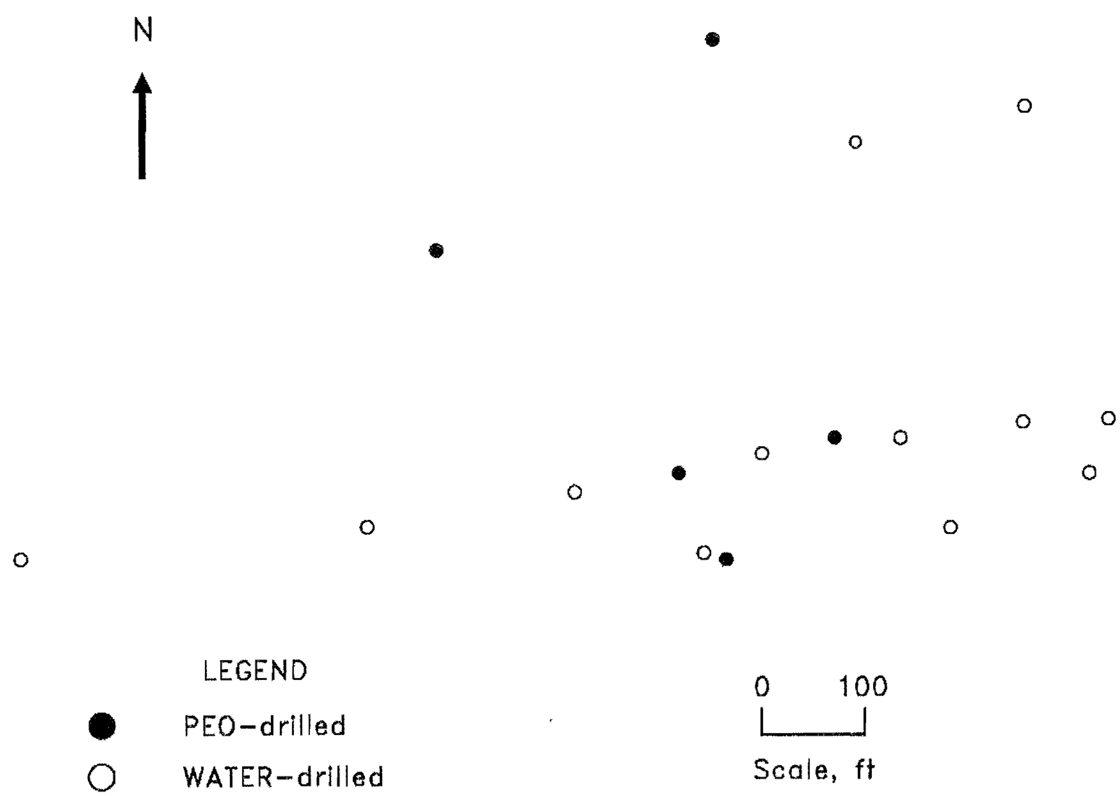

Figure 7.—Pennsylvania relative drill-hole locations.

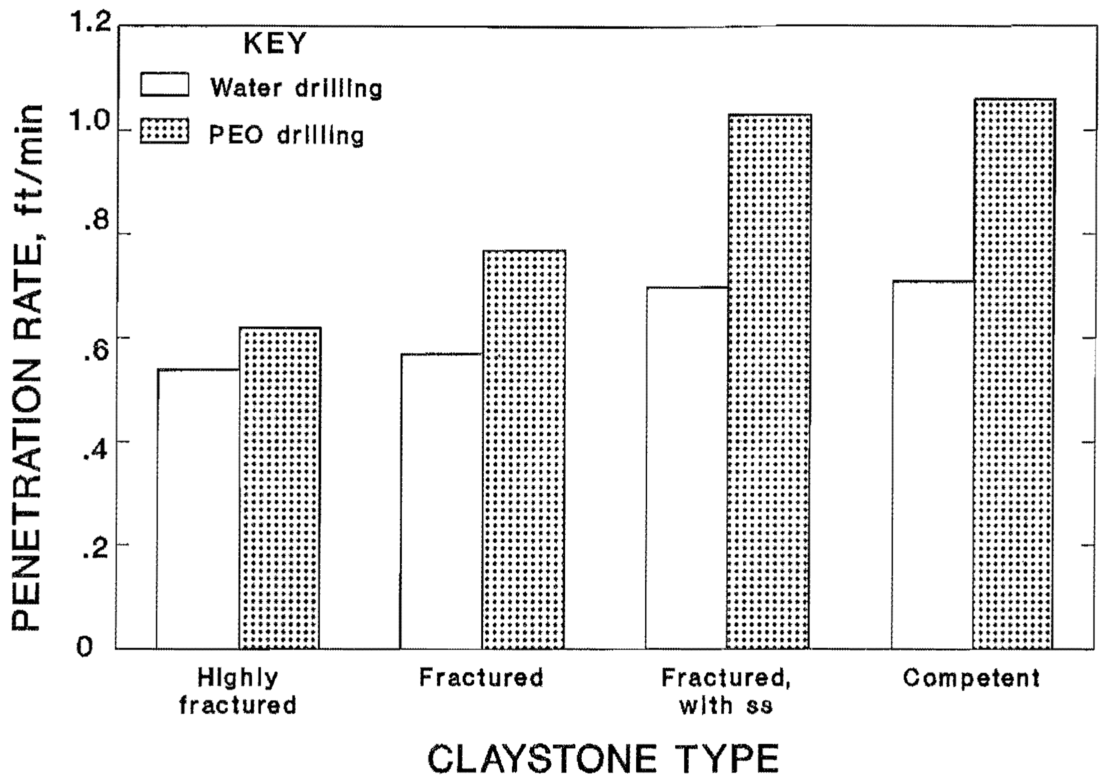

Figure 8.—PEO versus water drilling for specific Pennsylvania rock lithologies (ss = sandstone).

ADDITIONAL BENEFITS

Additional benefits of drilling with PEO solutions indicated by the drillers in both Ohio and Pennsylvania include a noticeable decrease in drill stem chatter, flocculation of fine silt and clay particles in the effluent, and the sealing of minor low-pressure leaks. Because the Pennsylvania drilling was done in the autumn, some difficulty was encountered with flow of the PEO concentrate solution as it thickened and flowed more slowly with the colder temperatures. These concerns need to be addressed if drilling is done under similar conditions.

DRILLING COST ANALYSIS

Drilling costs are a major expense in exploratory and AML drilling programs. With limited budgets, State AML agencies are aware of the high costs of drilling to define and delineate abandoned underground mine workings. High costs also concern coal companies engaged in exploratory drilling to define new coal reserves. The estimated cost of exploratory drilling in the United States alone was over $45 million for 1987 (*5*).

ADDITIONAL DRILLING COSTS WITH PEO SOLUTIONS

Using the Ohio drilling tests as an example, the extra cost of drilling with PEO can be determined. The three holes drilled with PEO consumed 21.5 5-gal containers of concentrated (4,500-ppm) PEO solution. Preparation of the 107.5 gal of 4,500-ppm PEO at a cost of $5.40 per pound of PEO, with an additional $7.16 per gallon for ethylene glycol used in mixing, requires an additional cost of only $146.89 for the additives. Adding $40 for labor (estimated at $10 per hour for two workers for 2 h) brings the total cost to $186.89. Considering the entire depth of footage drilled with the 107.5 gal of concentrated PEO solutions (365.33 ft), the $186.89 total cost translates to a per-foot cost of $0.51 for the drilling additive.

DRILLING COST COMPARISON

The total number of containers of PEO concentrate used in the Pennsylvania tests was not recorded. However, data from the contract used to perform those drilling tests indicate that the bid was accepted for drilling at a cost of $10.22 per linear foot. Taking this as the baseline cost to drill with water alone, the cost to drill with PEO would be $10.73 ($10.22 + $0.51) per foot. Using these values, comparisons can be made for the range of penetration rate improvements and the resulting economic benefits obtained in both test programs. For these comparisons, it is assumed that while it costs $10.22 to drill 1 ft with water alone, when drilling with PEO, the cost of $10.73 covers drilling 1 ft plus the fraction of a foot equal to the percent improvement in penetration rate. For example, for a 20-pct improvement in penetration rate, the $10.73 would cover drilling 1.2 ft. The actual cost per foot would therefore be $8.94. Calculated costs for PEO drilling and percentage savings are given in table 5. In addition to the cost savings, increased penetration rates will allow a project to be completed in less time. To drill 100 ft at a penetration rate of 0.25 ft/min using water would take almost 7 h. With a PEO-induced penetration rate increase of 15 pct, that time would be reduced to less than 6 h; a 25-pct improvement would reduce time to about 5.5 h; a 40-pct increase to 4.75 h; and a 50-pct increase to less than 4.5 h to drill 100 ft. The cost savings, coupled with the decrease in time to complete a project, would be a considerable advantage to those drilling coal measure rocks, whether in fractured or unfractured rock.

Table 5.—Drilling cost savings using PEO, based on water drilling costs of $10.22 per foot

Penetration rate improvement using PEO, pct	Cost to drill, $/ft	Cost savings, pct
15	9.33	8.7
20	8.94	12.5
25	8.58	16.0
30	8.25	19.2
35	7.95	22.2
40	7.66	25.0
45	7.40	27.6
50	7.15	30.0

SUMMARY AND CONCLUSIONS

Zeta potentials were measured for a variety of coal measure rocks. For most rocks, the minimum concentrations of PEO at which the zeta potential becomes zero was found to be 7.5 ppm. To allow for poor drilling water quality and drilling particulate flocculation in recirculated water, a concentration of 15 ppm PEO is recommended.

As was the case under controlled laboratory conditions, the results of comparative field drilling tests with PEO solutions and water alone on coal measure rocks indicate that penetration rates can be substantially improved with PEO solutions. Penetration rate improvements from 15 to 50 pct were demonstrated in two separate field drilling tests in coal measure rocks. Such improvements more than offset the small additional cost of the PEO and result in about a 10- to 30-pct savings in drilling costs. Such savings would help reduce overall costs for drilling coal measure rocks to delineate the extent of underground mine voids in AML programs and to define coal reserves in exploration drilling programs. This finding will benefit not only those drilling to delineate underground voids on AML lands and those exploring for coal, but also those exploring for other mineral commodities.

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APPENDIX.—PEO REQUIREMENTS AND CHEMICAL ANALYSES OF MATERIALS RECEIVED

INFORMATION ABOUT PEO

Description of PEO

The material used in the drilling tests, polyethylene oxide (PEO), is a high-molecular-weight, long-molecular-chain, nonionic polymer. It is available in a solid form as a white powder. All laboratory and field experiments conducted by the Bureau have employed the 5-million-molecular-weight variety of PEO, which is available under the brand name "Polyox," WSR Coagulant Grade, from the Union Carbide Corp. (Specialty Chemicals Division) of Lisle, IL. There are also other molecular weights available, ranging from 100,000 to 6 million; however, these have not been used in any Bureau field drilling tests to date.

Handling and Safety Considerations

PEO in powder form is an inert, relatively nontoxic, and nonhazardous substance that has a slight ammoniacal odor. While PEO polymer can be handled without elaborate equipment, care should be taken to avoid inhalation, swallowing, or direct eye contact with this irritant, nuisance dust (a simple particle-filtering face mask and normal handling precautions would be sufficient). The Mine Safety and Health Administration (MSHA) conducted several tests for the presence of ethylene oxide in the air from either the PEO or ethylene glycol as workers were mixing the PEO powder into water, as workers were dispensing the fluid, during rotary drilling with the fluid, during loading of ammonium nitrate and fuel oil (ANFO) explosives, and after blasting at an operating mine on the Minnesota Iron Range. MSHA concluded that no ethylene oxide or other potential chemical hazards attributable to the PEO solutions were present. Given these facts, the use of dilute PEO solutions for drilling additives poses no risk of toxicity to workers. An exception would be the potential slippage-and-fall hazard if solutions are spilled, as described below.

When the powder is mixed with water at any concentration, the slight irritation, odor, and contact effects that exist for the powder are effectively nullified in the aqueous solution. Whenever PEO is mixed with water, however, the slurry or solution becomes very slippery. If PEO powder on the floor becomes wet, or if an aqueous solution of PEO spills on the floor, a potential slippage-and-fall hazard is created. Although the severity of this potential hazard is reduced for dilute PEO solutions, it is nevertheless a concern for even such low concentrations as 10 ppm. Therefore, careful handling and transport practices are recommended.

With regard to possible corrosive effects, concentrated solutions of 0.5 pct of PEO in water can cause a slight but noticeable rusting or corrosion of metal containers. This is due to an oxidative breakdown reaction that effectively reduces the length of PEO molecular chains, particularly in the presence of iron. For this reason, it is recommended that concentrated solutions of PEO be stored in plastic containers prior to dilution for use. However, in the dilute concentrations used in this drilling application, the opposite seems to be true. In numerous drilling tests in the field using 15 ppm PEO in the drilling solution, drill bits showed markedly less corrosion than comparable bits drilled with water. Also, none of the field operators have noticed any corrosion in their drill rigs' holding tanks.

PEO Mixing Procedures

Preferred Method

The following procedure will yield 25 gal of PEO concentrate solution (4,500 ppm), which makes 7,500 gal of 15-ppm drilling fluid. These measures can be adjusted proportionally for larger or smaller volumes.

To convert parts per million to percent (weight divided by volume), use the following formula:

$$4{,}500 \text{ ppm} = 4{,}500 \text{ mg/L} = 4.5 \text{ g/L} = 0.45 \text{ pct.}$$

To prepare a 4,500 ppm solution, follow this procedure:

1. Weigh out 425 g of PEO polymer.
2. Measure out 750 mL of ethylene glycol (0.08 pct). This is used to make mixing of the PEO easier. (If ethylene glycol is not readily available, conventional engine antifreeze stock, which is about 95 pct ethylene glycol, would be an appropriate substitute.)
3. Add PEO to ethylene glycol while stirring to make a slurry. This will make slightly more than 1 L. The consistency should be that of cake batter.
4. Fill barrel (55-gal drum) with 25 gal (95 L) of water. (Barrel should have a spigot or shutoff valve mounted on the bottom or on the side close to the bottom so that after the PEO solution is mixed it can be emptied or pumped out of the barrel.)
5. Insert electric motor with stirrer into water. A sufficient speed to create a rapidly rotating vortex in the barrel is essential, with a 1,750-rpm motor preferred, using impeller blades and shaft designed for this speed.
6. Turn on electric motor to begin stirring, add PEO and ethylene glycol slurry directly into the stirred water, and continue stirring for 3 to 5 min. The concentrate will have a "slimy," thick consistency.

7. Dispense this 4,500-ppm solution concentrate into *plastic* containers. (The concentrate can be emptied by gravity flow using the spigot or shutoff valve to halt the flow of polymer, or a mechanical or electric fluid pump may be utilized. WARNING: If no method of cutting off the flow of polymer solution is used as described, once the pouring of the solution begins, *all* 25 gal of the concentrate may be poured out of the barrel in an uncontrollable manner.)

8. Store the 4,500-ppm solution concentrate in an environment that avoids extreme temperature variations. NOTE: Freezing of the aqueous solution drastically reduces the chain-length of the polymer molecules, which reduces its rock-drilling effectiveness. (At temperatures near the freezing of water, the polymer concentrate becomes thicker and more difficult to pour.)

Alternate Method

Using an aspiration-type Penberthy funnel (otherwise known as a "jet mixer," often used to prepare bentonite solutions for drilling muds), PEO can be introduced either as a dry powder or as a glycol slurry in a stream of water. More concentrated solutions may be possible. To determine concentration of solution (parts per million), divide weight of polymer used (in milligrams) by volume of water in barrel (in liters). The procedure is as follows:

1. Measure out the same amounts of PEO powder and ethylene glycol as described in steps 1 and 2 above.

2. Turn on water hose attached to the funnel to begin filling barrel with water (8- to 20-gpm flow is adequate).

3. Pour the PEO powder or PEO and ethylene glycol slurry into the funnel rapidly. The PEO mixes quite rapidly and thoroughly by this method.

4. Follow same procedure for stirring and dispensing as in steps 4 through 8 above.

Preparation as a Drilling Fluid

The concentrated solutions can easily be transported to the drilling site in 5-gal plastic containers. Any number of these containers can be added to a water tank or reservoir to prepare the required solution concentration. Additional containers can be added at any time when the water supply becomes depleted, when water is lost downhole, or during extreme conditions when evaporation is excessive. Any type of water reservoir would be acceptable, from water tanks to troughs (as used in the Ohio field tests, described in the text).

CHEMICAL ANALYSES SUMMARY

Tables A-1 through A-9 summarize the required threshold PEO solution concentrations for the rocks obtained from AML State coordinators and mine operators (in Minneapolis tap water and local drilling water when applicable), the chemical analyses of the waters received, and the chemical analyses of the rocks received (separated by type). These tables may be utilized following the techniques described in the text of this report.

Table A-1.—PEO concentrations for rocks and waters received

State and location	Lithology	Depth, ft	Sample No.	PEO conc, ppm	
				Local water	Tap water
Alabama:					
Carbon Hill Mine, Carbon Hill water	Coal	20.73	ND	10.0	7.5
Do.	Coarse sandstone	21.92	6518	7.5	7.5
Do.	Shale	37.18	6972	10.0	7.5
Do.	Sandstone with shale streaks	50.58	6519	7.5	7.5
Do.	Shale with sandstone streaks	53.76	6973	7.5	7.5
Labuco Mine, Labuco water	Shale	200	6974	7.5	5.0
Do.	Sandrock	200	6517	7.5	5.0
Do.	Fine-grained sandrock	200	6516	7.5	5.0
Colorado:					
Coal Bank Canyon near Raton Creek, Purgatoire River water	Basalt	Grab	7775	7.5	7.5
Do.	do.	Grab	7776	7.5	7.5
Picketwire Valley, Purgatoire River water	Sandstone	Grab	7777	7.5	7.5
Do.	Limestone	Grab	7778	7.5	5.0
Do.	Siltstone	Grab	7779	NS	7.5
Do.	Graywacke	Grab	7780	NS	7.5
Primero Mine area, Purgatoire River water	Sandstone	Grab	7772	10.0	10.0
Do.	do.	Grab	7773	NS	7.5
Do.	Coal	Grab	ND	7.5	7.5
Illinois:					
Cedar Creek mine area 11, Cedar Creek water	Brown shale	Grab	6977	7.5	5.0
Do.	Light gray shale	Grab	6978	7.5	5.0
Do.	do.	Grab	6979	7.5	5.0
Do.	Dark gray shale	Grab	6980	7.5	5.0
Do.	Coal	Grab	ND	10.0	7.5
Freeman United Industry Mine, Freeman water	Sandrock with gray shale	Grab	6515	5.0	5.0
Do.	Freeman coal	Grab	ND	7.5	7.5
Midland Coal Co., permit 170, Midland water	Shale	Grab	6975	7.5	7.5
Do.	Limestone	Grab	7510	10.0	5.0
Do.	Slate above coal	Grab	6976	7.5	7.5
Do.	Coal	Grab	ND	10.0	7.5
Kentucky:					
Geological Survey, no water	Limestone	Grab	8450	NS	5.0
Do.	do.	Grab	8151	NS	7.5
Do.	do.	Grab	8152	NS	5.0
Do.	Shale	Grab	8149	NS	5.0
Do.	do.	Grab	8150	NS	5.0
Do.	Sandstone	Grab	8153	NS	5.0
Great Western Coal Co., Harlan County, no water	do.	42.17	6981	NS	7.5
Do.	Silt (sandshale)	73.92	6982	NS	7.5
Do.	do.	117.83	6983	NS	7.5
Do.	Shale	170.75	7345	NS	10.0
Do.	do.	231.92	6984	NS	7.5
Do.	Silt	262.25	6985	NS	10.0
Do.	Shale	321.92	7342	NS	10.0
Do.	Sandstone	351.67	7343	NS	7.5
Do.	Silt	414.25	7344	NS	7.5
Do.	do.	465.5	8154	NS	5.0
Do.	Sandshale	510.0	8155	NS	5.0
Do.	Shale	563.92	8156	NS	5.0
Do.	Sandshale	620.67	8157	NS	5.0
Montana:					
Decker Coal Co., Decker Mine water	Surface soil	Grab	8435	5.0	5.0
Do.	Siltstone	Grab	8431	7.5	7.5
Do.	Sandstone	Grab	8429	7.5	5.0
Do.	Sandy shale	Grab	8430	7.5	5.0
Do.	Limestone	Grab	8428	7.5	5.0
Do.	Coal	Grab	ND	5.0	7.5

See notes at end of table.

Table A-1.—PEO concentrations for rocks and waters received—Continued

State and location	Lithology	Depth, ft	Sample No.	PEO conc, ppm Local water	PEO conc, ppm Tap water
Montana—Continued					
Lee Techni-Coal, hole 62720-2C, private well					
PW-004 water, Fort Union Formation	Sandstone	89.8	8366	5.0	5.0
Do.	Shale	93.5	8367	5.0	5.0
Do.	Sandstone	131.3	8368	5.0	7.5
Do.	.. do.	218.5	8369	5.0	5.0
Spring Creek Coal Co., main dust control					
pond water	Gray shale	(1)	8434	7.5	5.0
Do.	Claystone	(2)	8432	7.5	5.0
Do.	Shale	(3)	8433	7.5	5.0
Westmoreland Resources, Absolaka Mine,					
Madison Formation water	Brown rock	Grab	8365	5.0	5.0
Do.	Gray rock	Grab	8364	5.0	5.0
Ohio:					
COCC, water sample from sump	Limestone	[4]68	7771	15.0	5.0
Do.	Shaley clay	[4]48	7769	10.0	5.0
Do.	Sandstone	[4]85	7770	10.0	7.5
Do.	Clay	[4]75	7768	15.0	7.5
COCC hole JMB 26-20,[5] no water.	Chips	.0	8445	NS	5.0
Do.	Limestone	18.0	8437	NS	5.0
Do.	Shale	20.33	8447	NS	5.0
Do.	Limestone	74.75	8439	NS	7.5
Do.	Shale	78.17	8446	NS	5.0
Do.	Limestone	101.17	8438	NS	5.0
Do.	Shale	103.67	8440	NS	5.0
Do.	Limestone	108.08	8449	NS	5.0
Do.	Claystone	117.5	8442	NS	5.0
Do.	Limestone	123.92	8436	NS	7.5
Do.	Claystone	126.08	8443	NS	5.0
Do.	Sandstone	133.92	8444	NS	5.0
Do.	Shale	142.58	8441	NS	5.0
Do.	.. do.	153.83	8448	NS	5.0
COCC hole JMB 35-20,[5] no water	Chips	.0	7994	NS	5.0
Do.	Shale	18.0	7991	NS	5.0
Do.	Limestone	27.92	7988	NS	5.0
Do.	Shale	33.33	7996	NS	5.0
Do.	Limestone	85.17	7986	NS	5.0
Do.	Shale	89.58	7995	NS	5.0
Do.	Limestone	110.58	7987	NS	5.0
Do.	Shale	115.08	7983	NS	5.0
Do.	Limestone	117.25	7992	NS	5.0
Do.	Claystone	127.75	7984	NS	5.0
Do.	Limestone	131.92	7985	NS	5.0
Do.	Claystone	136.08	7990	NS	5.0
Do.	Sandstone	146.17	7993	NS	5.0
Do.	Shale	157.17	7989	NS	5.0
Do.	.. do.	166.67	7982	NS	5.0
Corehole 2548, water sample OH-4, Campaign					
Creek, Gallia County	Mudstone	96	6629	7.5	10.0
Do.	Sandstone	258	7348	7.5	5.0
Do.	Limestone	278	7512	7.5	10.0
Do.	Sandstone	295	7349	7.5	7.5
Do.	Shale	326	6630	7.5	7.5
Do.	Coal	343	ND	10.0	10.0
Do.	Limestone	465	7517	7.5	7.5
Do.	Shale	576	6631	5.0	7.5

See notes at end of table.

Table A-1.—PEO concentrations for rocks and waters received—Continued

State and location	Lithology	Depth, ft	Sample No.	PEO conc, ppm Local water	PEO conc, ppm Tap water
Ohio—Continued					
Corehole 2562, water sample OH-2, Wheeling Creek, Belmont County	Mudstone	128	6281	5.0	5.0
Do.	Shale	146	6624	7.5	10.0
Do.	Coal	196	ND	7.5	7.5
Do.	Limestone	251	7515	10.0	10.0
Do.	Shale, coal	297	6282	7.5	10.0
Do.	Sandstone	408	6509	7.5	7.5
Do.	Mudstone	569	6625	7.5	10.0
Do.	Siltstone	578	6626	7.5	7.5
Corehole 2567, water sample OH-3, Salt Fork Creek, Guernsey County	Flint clay	109	6283	7.5	10.0
Do.	Shale	234	6622	7.5	10.0
Do.	Bone coal	352	ND	7.5	7.5
Do.	Limestone	389	7516	7.5	7.5
Do.	Sandstone	448	6510	7.5	7.5
Do.	.. do.	567	6511	5.0	7.5
Do.	Shale	617	6623	7.5	5.0
Do.	Conglomerate	785	6285	7.5	7.5
Corehole 2599, no water	Limestone	49	7518	NS	10.0
Do.	Shale	114	6634	NS	7.5
Do.	Underclay	149	6628	NS	7.5
Do.	Shale	209	6627	NS	5.0
Do.	Sandstone	288	6512	NS	7.5
Do.	Limestone	328	7513	NS	7.5
Do.	Coal	406	ND	NS	10.0
Do.	Sandstone	445	6513	NS	7.5
Corehole 2617, water sample OH-1, Cold Run tributary, Columbiana County	Limestone	78	7514	7.5	10.0
Do.	Shale	91	6632	7.5	10.0
Do.	Sandstone	156	6514	7.5	7.5
Do.	Limestone	189	7511	7.5	7.5
Do.	Shale	264	6633	7.5	5.0
Do.	Sandstone	316	7346	7.5	7.5
Do.	Shale	392	7347	7.5	7.5
Do.	Sandstone	488	6284	7.5	7.5
Pennsylvania:					
Anthracite Region, hole 28, no water	Shale	94.6	7157	NS	10.0
Do.	Sandstone	103.0	7153	NS	7.5
Do.	.. do.	110.0	7154	NS	7.5
Do.	Coal	130.4	ND	NS	5.0
Do.	Carbonaceous shale	136.6	7155	NS	7.5
Do.	Coal	151.4	ND	NS	5.0
Do.	Sandstone	151.8	7156	NS	7.5
Anthracite Region, hole CH-1, no water	.. do.	14.0	8356	NS	7.5
Do.	Conglomerate	25.0	8357	NS	7.5
Do.	.. do.	31.4	7354	NS	7.5
Do.	Coal	35.3	ND	NS	5.0
Do.	Sandstone	49.4	7355	NS	7.5
Do.	Claystone	57.5	7158	NS	7.5
Do.	Limey, sandy siltstone	61.4	7159	NS	7.5
Eastern Bituminous Region, hole 7, no water	Shaley sandstone	19.0	7350	NS	7.5
Do.	Sandstone	33.6	7351	NS	10.0
Do.	Limestone	38.4	7509	NS	7.5
Eastern Bituminous Region, hole 7A, no water	Sandstone	34.4	8358	NS	7.5
Do.	Coal	37.1	ND	NS	5.0
Do.	Limestone	44.1	8359	NS	7.5
Do.	Shale	59.6	8360	NS	5.0
Do.	.. do.	66.0	8361	NS	7.5
Do.	Carbonaceous shale	87.6	8362	NS	7.5
Do.	Clayshale	112.0	8363	NS	5.0

See notes at end of table.

Table A-1.—PEO concentrations for rocks and waters received—Continued

State and location	Lithology	Depth, ft	Sample No.	PEO conc, ppm Local water	PEO conc, ppm Tap water
Pennsylvania—Continued					
Eastern Bituminous Region, hole 17, no water	Sandstone	35.1	6522	NS	7.5
Do.	.. do.	66.6	6272	NS	7.5
Do.	Limestone	74.7	7508	NS	7.5
Do.	Siltstone	81.0	6273	NS	10.0
Do.	Sandstone	93.1	6523	NS	10.0
Do.	Shale	105.0	6274	NS	10.0
Do.	.. do.	142.8	7165	NS	10.0
Do.	Carbonaceous shale	161.5	6275	NS	10.0
Do.	Coal	165.5	ND	NS	10.0
Do.	Claystone	167.4	6276	NS	7.5
Western Bituminous Region, hole 1, no water.	.. do.	17.1	8316	NS	7.5
Do.	Sandstone	23.5	8317	NS	7.5
Do.	Silty shale	31.0	8318	NS	5.0
Do.	Sandy shale	33.0	8319	NS	7.5
Do.	Coal	40.8	ND	NS	10.0
Western Bituminous Region, hole 7, Burkett elementary school area water	Sandstone	57.7	6521	7.5	7.5
Do.	Claystone	70.0	6277	7.5	7.5
Do.	Sandy shale	72.2	6278	7.5	10.0
Do.	Sandstone	99.6	6279	7.5	10.0
Do.	Carbonaceous shale	123.2	6280	7.5	7.5
Do.	Coal, Pittsburgh Seam	140.0	ND	7.5	7.5
Do.	Limey claystone	144.0	7166	5.0	7.5
Western Bituminous Region, hole 7, Mount Oliver Borough subsidence area water	Sandstone	57.7	6521	7.5	7.5
Do.	Claystone	70.0	6277	7.5	7.5
Do.	Sandy shale	72.2	6278	7.5	10.0
Do.	Sandstone	99.6	6279	7.5	10.0
Do.	Carbonaceous shale	123.2	6280	7.5	7.5
Do.	Coal	140.0	ND	10.0	7.5
Do.	Limey claystone	144.0	7166	7.5	7.5
Western Bituminous Region, hole 24, no water	Sandstone	32.0	8320	NS	5.0
Do.	Limestone	47.1	8321	NS	5.0
Do.	Carbonaceous shale	77.5	8322	NS	7.5
Do.	Claystone	87.6	8323	NS	7.5
Do.	Limestone	103.4	8324	NS	5.0
Do.	Shale	139.6	8325	NS	5.0
Do.	Carbonaceous shale	170.0	8326	NS	5.0
Do.	Shale	227.6	8327	NS	7.5
Do.	.. do.	255.3	8328	NS	5.0
Do.	Carbonaceous shale	267.7	8329	NS	7.5
Western Bituminous Region, hole C8, Crabtree mine fire water	Shale	37.8	7352	1.0	5.0
Do.	Sandstone	40.6	6520	5.0	5.0
Do.	Shale	49.0	7353	5.0	5.0
West Virginia:					
Fayette County, New River Formation, no water	Sandstone	Grab	8308	NS	5.0
Nicholas County, Kanawha Formation, no water	Sandstone, shale	Grab	8314	NS	7.5
Hole 191-71, Dunkard Group, no water	Mudstone	118.0	8312	NS	7.5
Hole 191-71, Conemaugh Group, no water	Red mudstone	712.0	8315	NS	7.5
Do.	Bush Creek shale	1,065.0	8309	NS	7.5
Do.	Sandstone	1,142.0	8310	NS	7.5
Hole 191-71, Allegheny Group, no water	Rooted underclay	1,410.0	8313	NS	7.5
Hole 191-81, Monongahela Group, no water	Limestone	383.5	8311	NS	7.5

ND Not determined, owing to proprietary considerations.
NS No water samples received; therefore, test not conducted.
[1]Dragline overburden.
[2]Upper bench.
[3]Bench 1.
[4]Above coal.
[5]Hole in field test, discussed in text.

Table A-2.—Chemical analyses of waters received from AML States, parts per million

Element or compound	Alabama		Colorado:	Illinois		
	Carbon Hill	Labuco	Purgatoire River	Cedar Creek	Freeman	Midland
Al^{3+}	<0.25	0.41	<0.25	<0.25	<0.25	<0.25
Ca^{2+}	28	38	32	38	440	89
Cl^-	.63	1.9	.38	5	24	450
Fe^{3+}	<.25	<.25	<.25	<.25	<.25	<.25
Mg^{2+}	20	18	5.7	13	84	61
Mn^{2+}	<.25	<.20	<.25	<.20	<.20	<.20
Na^+	17	7.0	5.9	13	39	781
NO_3^-	1.9	<.25	<.25	<.25	<.25	<.25
Si^{4+}	4.7	7.2	3.9	.71	1.7	<.25
SO_4^{-2}	92	130	16	93	1,348	93

Element or compound	Montana				
	Decker Mine	Decker Mine[1]	Lee Techni-Coal	Spring Creek pond	Westmoreland
Al^{3+}	<2.0	<0.25	<0.25	<0.25	<0.25
Ca^{2+}	10	242	4.7	345	56
Cl^-	31	18	6.5	134	14
Fe^{3+}	<.25	<.25	<.25	<.25	<.25
Mg^{2+}	43	98	4.9	56	15
Mn^{2+}	<.1	<.1	<.1	<.1	<.25
Na^+	690	108	488	110	9
NO_3^-	1.9	40	1.8	<.5	10
Si^{4+}	12	6	4.4	22	3
SO_4^{-2}	403	1,200	175	1,108	90

Element or compound	Ohio				
	COCC sump	OH-4, Campaign Creek	OH-2, Wheeling Creek	OH-3, Salt Fork Creek	OH-1, Cold Run trib.
Al^{3+}	<2.00	<0.25	1.2	<0.25	1.1
Ca^{2+}	86	56	27	70	197
Cl^-	1.9	14	4.4	6.9	11
Fe^{3+}	<.25	<.25	1.1	<.25	<.25
Mg^{2+}	20	15	5.4	21	88
Mn^{2+}	<.1	<.25	<.25	<.25	<.25
Na^+	4.8	9	5	9	73
NO_3^-	1.0	10	1.7	1	1.4
Si^{4+}	3.8	3	6.3	3.9	2.6
SO_4^{-2}	130	90	29	162	708

Element or compound	Pennsylvania			Minnesota	
	Western hole 7, Mount Oliver	Western hole 7, Burkett	Western hole C8, Crabtree	Minneapolis tap water, Aug. 1989	Minneapolis tap water, Aug. 1990
Al^{3+}	<0.25	<0.25	15	0.29	<2.00
Ca^{2+}	41	39	94	22	21
Cl^-	19	12	.6	14	21
Fe^{3+}	<.25	<.25	.41	<.25	<.25
Mg^{2+}	8	9	44	3.7	7
Mn^{2+}	<.25	<.25	10	<.25	<.1
Na^+	15	18	4.1	7	10
NO_3^-	2.3	2.8	<.25	1.2	2.5
Si^{4+}	2.9	2.8	19	3	8
SO_4^{-2}	93	117	480	26	33

[1]MBMG water.

Table A-3.—Chemical analyses of claystones received from AML States, percent

Compound	Montana: Spring Creek, 8432	Ohio: COCC 7768	Ohio: COCC 7769	Ohio: COCC corehole JMB 26-20, 8442	Ohio: COCC corehole JMB 26-20, 8443	Ohio: COCC corehole JMB 35-20, 7984	Ohio: COCC corehole JMB 35-20, 7990	Ohio: Corehole 2567, 6283	Ohio: Corehole 2599, 6628
Al_2O_3	7.37	10.2	12.47	11.71	6.42	2.64	5.86	3.21	25.69
CaO	17.77	14.97	7.13	.53	20.29	59.43	21.4	26.16	.07
Fe_2O_3	14.16	5.58	5.01	3.72	2.72	2.72	2.57	6.29	1.39
K_2O	1.21	2.17	3.25	2.53	1.57	.71	1.45	.59	1.92
MgO	8.46	5.14	4.64	2.65	10.28	21.85	10.45	14.42	.46
MnO_2	.33	.14	.05	<.01	.08	.17	.11	.27	<.01
Na_2O	.4	.36	.39	.98	.43	.35	.43	.08	.51
P_2O_5	.13	.09	.1	.09	.1	.14	.11	.1	.05
SiO_2	21.18	38.5	50.27	68.23	29.95	11.76	27.38	7.27	56.9
TiO_2	.3	.55	.7	.72	.28	.15	.3	<.2	1.83
LOI, 105° C	1.6	2.4	3.2	2.9	1.3	.53	.88	.22	1.1
LOI, 1,000° C	29.3	21.8	15.4	6.5	29.5	38.0	30.0	40.7	9.3

Compound	Pennsylvania: Anthracite hole CH-1, 7158	Pennsylvania: Eastern hole 7A, 8363	Pennsylvania: Eastern hole 17, 6276	Pennsylvania: Western hole 1, 8316	Pennsylvania: Western hole 7, 6277	Pennsylvania: Western hole 7, 7166	Pennsylvania: Western hole 24, 8323	West Virginia: hole 191-71, 8313
Al_2O_3	22.48	24.93	18.51	16.81	12.85	14.73	17.57	20.78
CaO	.21	.28	.14	.35	21.68	10.77	.35	.15
Fe_2O_3	2.57	1.72	1.36	1.72	5.29	3.72	7.44	2.0
K_2O	4.1	2.89	2.41	2.65	2.05	2.05	4.82	1.69
MgO	.83	.68	.53	.71	1.24	5.97	3.15	.71
MnO_2	<.01	<.01	<.01	.02	.3	.17	.02	.02
Na_2O	.67	.16	.19	.16	.13	.35	.3	.35
P_2O_5	.04	.05	.03	.03	.09	.05	.04	.03
SiO_2	63.74	57.54	66.95	71.44	33.8	39.14	55.19	63.10
TiO_2	.95	1.27	2.34	.38	.55	.63	.82	1.38
LOI, 105° C	.81	1.5	.53	.46	.68	.8	2.2	.86
LOI, 1,000° C	5.4	10.0	6.1	5.8	19.4	20.2	8.0	8.3

LOI Loss on ignition.

Table A-4.—Chemical analyses of limestones received from AML States, percent

Compound	Colorado: Picketwire Valley, 7778	Illinois: Midland Coal, 7510	Kentucky: Geological Survey			Montana: Decker Coal, 8428	Ohio: COCC, 7771
			8450	8151	8152		
Al_2O_3	4.91	6.61	1.61	1.27	2.08	8.88	0.79
$CaCO_3$	18.98	25.25	86.4	83.16	58.19	16.48	86.4
Fe_2O_3	32.75	15.59	1.43	1.72	15.16	15.44	.46
K_2CO_3	1.17	1.59	.21	.32	.35	1.94	.21
$MgCO_3$	3.29	6.94	2.22	3.12	4.86	12.49	5.2
$MnCO_3$	1.09	.88	.17	.36	.65	.23	.21
Na_2CO_3	.6	.92	.07	<.05	.14	.41	.14
P_2O_5	1.51	.33	.24	.19	.14	.09	.2
SiO_2	20.75	31.23	3.85	5.56	13.48	29.52	4.06
TiO_2	.23	.48	.05	.07	.13	.38	.07
LOI, 105° C	.59	.39	.17	.16	.31	1.5	.19
LOI, 1,000° C	23.1	23.3	41.5	40.8	34.3	26.5	42.2

Compound	Ohio									
	COCC corehole JMB 26-20					COCC corehole JMB 35-20				
	8436	8437	8438	8439	8449	7985	7986	7987	7988	7992
Al_2O_3	3.02	5.48	3.4	2.27	2.83	5.67	5.48	1.89	7.37	2.27
$CaCO_3$	59.68	35.96	73.92	77.17	41.45	20.43	49.45	66.43	50.69	47.95
Fe_2O_3	2.15	7.44	.83	1.19	2.86	2.15	3.15	1.14	2.57	2.86
K_2CO_3	.76	.88	.71	.41	.39	1.33	1.24	.46	2.3	.57
$MgCO_3$	19.08	22.2	6.94	9.36	29.13	7.63	16.99	13.18	6.94	31.21
$MnCO_3$	.1	.4	.13	.23	.15	.11	.19	.17	.23	.21
Na_2CO_3	.32	.23	.37	.14	.35	.47	.48	.3	.48	.37
P_2O_5	.15	.12	.18	.18	.11	.09	.17	.2	.3	.11
SiO_2	9.63	20.96	14.12	9.41	13.9	35.72	21.18	14.55	27.38	12.83
TiO_2	.1	.15	.17	.1	.1	.4	.3	.13	.42	.12
LOI, 105° C	.58	.92	.61	.31	.4	1.4	.48	.25	1.1	.32
LOI, 1,000° C	38.7	31.3	37.2	39.4	37.8	26.2	32.4	37.3	27.6	38.9

Compound	Ohio							
	Corehole 2548		Corehole 2562,	Corehole 2567,	Corehole 2599		Corehole 2617	
	7512	7517	7515	7516	7513	7518	7511	7514
Al_2O_3	0.26	6.8	10.2	0.7	0.57	6.23	2.27	5.29
$CaCO_3$	87.9	40.71	29.97	87.2	83.7	64.4	73.9	68.7
Fe_2O_3	.92	5.58	3.57	1.72	1.57	2.86	3.86	2.15
K_2CO_3	<.05	.18	2.7	.23	.18	1.9	.78	1.6
$MgCO_3$	.31	1.9	2.6	1.8	1.6	3.1	1.8	2.6
$MnCO_3$	.15	.25	.23	.21	.19	.21	.31	.5
Na_2CO_3	<.05	1.8	2.1	<.05	<.05	.39	<.05	<.05
P_2O_5	.18	.04	.01	.22	.16	.17	.24	.33
SiO_2	.64	38.5	48.98	4.06	1.45	20.11	6.2	16.04
TiO_2	<.03	.48	.42	.0	<.03	.35	.1	.27
LOI, 105° C	.21	.44	.59	.32	.39	.91	.33	.69
LOI, 1,000° C	43.3	22.2	15.5	41.5	42.9	31.7	38.9	33.6

Compound	Pennsylvania					West Virginia: hole 191-81, 8311
	Eastern hole 7, 7509	Eastern hole 7A, 8359	Eastern hole 17, 7508	Western hole 24		
				8321	8324	
Al_2O_3	10.96	5.29	11.9	2.46	2.08	9.26
$CaCO_3$	29.97	65.18	32.96	59.68	76.92	31.22
Fe_2O_3	5.58	3.43	3.72	3.58	.76	2.86
K_2CO_3	2.7	1.43	3.5	.64	.49	2.83
$MgCO_3$	9.7	1.94	4.2	18.03	2.88	21.85
$MnCO_3$	.25	.13	.25	.46	.61	.17
Na_2CO_3	.16	.67	.18	.21	.14	1.13
P_2O_5	.01	.17	.07	.19	.19	.53
SiO_2	34.22	15.83	37.65	12.62	6.42	27.38
TiO_2	.62	.27	.6	.12	.08	.75
LOI, 105° C	.79	.38	.14	.18	.13	1.3
LOI, 1,000° C	24.0	33.8	20.1	37.5	40.0	26.2

LOI Loss on ignition.

Table A-5.—Chemical analyses of mudstones received from AML States, percent

Compound	Ohio: Corehole 2548, 6629	Ohio: Corehole 2562, 6281	Ohio: Corehole 2562, 6625	West Virginia: hole 191-71, 8312	West Virginia: hole 191-71, 8315
Al_2O_3	20.59	20.76	20.02	17.38	17.38
CaO	7.27	.29	.11	2.66	7.55
Fe_2O_3	7.58	8.29	3.57	11.01	8.44
K_2O	3.62	2.29	3.98	3.13	2.89
MgO	1.82	1.61	1.34	1.99	1.28
MnO_2	.08	.02	.03	.25	.19
Na_2O	.43	.73	.51	.49	.47
P_2O_5	.05	.03	.03	.07	.1
SiO_2	46.84	55.83	61.18	48.98	47.27
TiO_2	.88	1.13	1.25	.87	.88
LOI, 105° C	.84	1.4	.56	1.6	1.9
LOI, 1,000° C	11.7	8.7	6.0	12.3	12.7

LOI Loss on ignition.

Table A-6.—Chemical analyses of sandstones received from AML States, percent

Compound	Alabama: Carbon Hill Mine, 6518	Alabama: Carbon Hill Mine, 6519	Alabama: Labuco Mine, 6516	Alabama: Labuco Mine, 6517	Colorado: Picketwire Valley, 7777	Colorado: Primero Mine area, 7772	Colorado: Primero Mine area, 7773
Al_2O_3	7.18	10.58	11.71	7.74	11.33	7.18	11.15
CaO	<.1	.64	.17	14.41	.29	.2	.46
Fe_2O_3	1.17	4.72	3.0	4.43	3.72	.86	8.29
K_2O	1.21	1.69	1.93	1.33	.52	.22	.64
MgO	.33	1.21	.91	2.49	2.65	.18	.99
MnO_2	1.05	.09	<.05	.16	.11	.03	.03
Na_2O	.26	1.24	1.2	1.13	1.11	.09	.81
P_2O_5	.03	.07	.03	.04	.06	.04	.06
SiO_2	83.21	74.22	76.36	53.9	75.29	23.96	70.8
TiO_2	.72	.87	.87	.7	.55	.35	.53
LOI, 105° C	.27	.17	.18	.18	.82	.81	.88
LOI, 1,000° C	2.8	4.6	3.1	15.4	4.9	64.3	5.5

Compound	Illinois: Freeman Mine, 6515	Kentucky: Geological Survey, 8153	Kentucky: Great Western Coal, 6981	Kentucky: Great Western Coal, 7343	Montana: Decker Coal, 8429	Montana: Decker Coal, 8435	Montana: Lee Techni-Coal, 8366	Montana: Lee Techni-Coal, 8368	Montana: Lee Techni-Coal, 8369
Al_2O_3	10.01	5.1	8.69	4.53	8.88	10.01	9.26	10.01	9.45
CaO	3.78	.15	.34	.27	1.96	3.36	7.27	.21	7.41
Fe_2O_3	5.29	1.86	2.43	1.43	3.43	4.0	3.0	2.15	2.43
K_2O	1.57	.92	1.45	.37	1.93	1.93	2.05	2.41	2.17
MgO	1.06	2.49	.6	.4	1.04	1.82	3.81	1.09	3.81
MnO_2	<.05	.02	.05	.05	.08	.08	.09	.02	.08
Na_2O	1.2	.49	1.35	.88	.61	1.32	.8	.92	.88
P_2O_5	.06	.04	.04	.03	.1	.08	.08	.05	.08
SiO_2	69.3	87.7	84.28	86.42	71.44	66.74	58.39	80.43	57.11
TiO_2	.77	.45	.53	.4	.28	.52	.47	.48	.45
LOI, 105° C	.24	.32	.11	<.1	.71	2.3	.56	.38	.68
LOI, 1,000° C	6.6	1.8	2.7	1.6	9.5	10.6	16.7	2.6	11.3

Compound	Ohio: COCC, 7770	Ohio: COCC, Corehole JMB 26-20, 8444	Ohio: COCC, Corehole JMB 35-20, 7993	Ohio: COCC, Corehole 2548, 7348	Ohio: COCC, Corehole 2548, 7349	Ohio: Corehole 2562, 6509	Ohio: Corehole 2567, 6510	Ohio: Corehole 2567, 6511
Al_2O_3	9.63	6.23	10.58	5.86	12.28	5.86	6.8	9.45
CaO	8.95	1.54	.59	<.025	.39	.24	19.31	.15
Fe_2O_3	2.86	1.24	3.43	1.57	1.86	1.14	4.29	2.43
K_2O	1.45	.78	2.17	1.57	2.29	1.21	1.33	1.81
MgO	1.24	.5	1.39	.17	.5	.3	.85	.7
MnO_2	.16	<.01	<.01	.02	.02	<.05	.11	<.05
Na_2O	1.62	1.01	1.05	.54	.32	.51	.8	.36
P_2O_5	.06	.03	.03	.03	.03	.04	.05	.04
SiO_2	64.38	82.35	75.51	86.42	77.22	85.13	49.2	76.79
TiO_2	.45	.12	.47	<.25	.73	.22	.45	.83
LOI, 105° C	.24	.53	.83	.24	.1	.14	.16	.13
LOI, 1,000° C	10.1	3.6	3.8	2.1	3.5	1.8	17.8	3.3

LOI Loss on ignition.

Table A-6.—Chemical analyses of sandstones received from AML States, percent—Continued

Compound	Ohio: Corehole 2599, 6512	Ohio: Corehole 2599, 6513	Ohio: Corehole 2617, 6284	Ohio: Corehole 2617, 6514	Ohio: Corehole 2617, 7346	Pennsylvania: Anthracite hole 28, 7153	Pennsylvania: Anthracite hole 28, 7154	Pennsylvania: Anthracite hole 28, 7156
Al_2O_3	9.45	4.34	1.23	10.01	2.46	10.96	15.87	21.35
CaO	.25	.24	.2	.41	.57	.39	5.46	<.1
Fe_2O_3	3.43	2.15	.6	1.86	.83	3.57	13.73	4.15
K_2O	1.69	.88	.1	1.93	.61	1.93	2.89	3.98
MgO	.76	.25	.05	.63	.25	.83	3.65	1.66
MnO_2	<.05	<.05	<.01	<.05	.05	.08	.25	.03
Na_2O	.89	.09	<.05	.39	<.05	.19	.28	.18
P_2O_5	.07	.06	.02	.07	.02	.02	.05	.02
SiO_2	77.86	86.84	96.47	79.78	90.05	70.8	37.86	60.53
TiO_2	.5	.55	<.2	.75	<.25	1.18	1.22	.98
LOI, 105° C	.12	.37	<.01	.14	.1	.18	.4	.33
LOI, 1,000° C	3.4	2.7	.66	3.1	1.3	5.6	18.0	6.1

Compound	Pennsylvania: Anthracite hole CH-1, 7355	Anthracite hole CH-1, 8356	Eastern hole 7, 7350	Eastern hole 7, 7351	Eastern hole 7A, 8358	Eastern hole 17, 6272	Eastern hole 17, 6522	Eastern hole 17, 6523	Western hole 1, 8317	Western hole 7, 6279
Al_2O_3	9.63	6.42	15.1	7.37	4.16	4.91	8.31	17.0	14.92	15.49
CaO	<.025	.35	<.025	<.025	.07	.9	1.34	.24	.71	.34
Fe_2O_3	9.87	7.58	.84	2.0	.61	2.29	2.72	3.15	3.72	3.72
K_2O	1.69	.94	2.53	1.07	.53	.77	1.57	3.13	2.41	2.05
MgO	1.31	.91	1.28	.36	.13	.5	.73	1.13	1.53	1.29
MnO_2	.27	.17	.21	.06	<.01	.06	<.05	<.05	.06	.03
Na_2O	.35	.16	.2	1.29	.12	<.05	.07	.24	.16	1.62
P_2O_5	.04	.07	.05	.03	.03	.03	.04	.04	.04	.03
SiO_2	63.96	75.93	60.11	82.14	91.98	87.27	77.65	67.38	69.09	72.3
TiO_2	.83	.28	.95	.68	.33	<.2	.48	1.32	1.2.	1.27
LOI, 105° C	.22	.16	.5	.13	.11	.14	.13	.28	.49	.4
LOI, 1,000° C	7.3	5.6	2.6	3.9	1.3	3.0	4.1	4.9	5.8	4.4

Compound	Pennsylvania: Western hole 7, 6521	Pennsylvania: Western hole 24, 8320	Pennsylvania: Western hole C8, 6520	West Virginia: Fayette County, 8308	West Virginia: Nicholas County, 8314	West Virginia: Hole 191-71, 8310
Al_2O_3	20.02	9.82	9.26	14.92	17.19	9.63
CaO	.27	.35	.32	.21	.38	.57
Fe_2O_3	7.72	4.0	6.29	2.0	6.01	3.15
K_2O	3.49	1.69	1.21	2.53	3.98	2.05
MgO	2.82	.85	.6	.81	1.59	.75
MnO_2	.09	.03	.28	.03	.11	.06
Na_2O	.85	1.35	1.06	.12	.16	1.16
P_2O_5	.04	.04	.05	.04	.06	.05
SiO_2	57.11	80.21	73.8	72.08	61.6	78.5
TiO_2	1.25	.77	.53	1.05	1.28	.48
LOI, 105° C	.42	.13	.15	.23	.44	.15
LOI, 1,000° C	6.2	2.5	5.2	5.8	7.2	3.4

LOI Loss on ignition.

Table A-7.—Chemical analyses of shales received from AML States, percent

Compound	Alabama			Illinois				
	Carbon Hill Mine		Labuco Mine,	Cedar Creek Mine				Midland Coal,
	6972	6973	6974	6977	6978	6979	6980	6975
Al_2O_3	17.0	19.65	19.08	17.38	18.13	18.32	18.51	16.62
CaO	.43	.46	.45	.31	.39	.36	.43	1.4
Fe_2O_3	8.01	6.44	7.01	4.43	6.72	5.72	6.15	6.15
K_2O	3.01	4.1	3.86	2.77	3.25	2.89	3.01	2.77
MgO	1.53	1.99	1.99	1.14	2.16	1.82	1.99	1.82
MnO_2	.17	.08	.11	.03	.09	.05	.06	.21
Na_2O	.59	.85	1.08	1.23	1.16	1.35	1.25	1.02
P_2O_5	.06	.06	.06	.05	.06	.06	.07	.08
SiO_2	61.6	60.53	60.75	62.89	58.39	59.68	60.75	59.25
TiO_2	.92	1.07	1.07	.97	.88	.87	.98	.82
LOI, 105° C	.5	.34	.38	.25	.58	.4	.49	.4
LOI, 1000° C	8.1	6.3	5.9	6.0	6.5	5.8	6.0	8.5

Compound	Kentucky						Montana	
	Geological Survey		Great Western Coal				Decker Coal,	Lee Techni-Coal,
	8149	8150	6984	7342	7345	8156	8430	8367
Al_2O_3	16.62	15.3	8.12	16.25	22.48	21.72	10.39	15.11
CaO	.55	.69	3.08	.27	.84	.42	2.24	6.72
Fe_2O_3	6.72	7.15	31.17	6.15	4.72	7.86	2.57	4.72
K_2O	3.01	2.53	1.57	3.13	4.46	4.22	2.41	3.74
MgO	1.53	1.51	4.64	1.39	2.32	2.16	2.32	4.81
MnO_2	.14	.19	.66	.11	.08	.21	.05	.09
Na_2O	.9	.86	.3	1.04	.74	.46	1.48	.59
P_2O_5	.06	.06	.12	.06	.06	.07	.06	.06
SiO_2	61.39	62.89	20.75	54.33	53.05	51.76	65.67	53.05
TiO_2	1.03	1.0	.3	.85	.93	.87	.45	.63
LOI, 105° C	.65	.59	.35	.41	.53	.47	.99	1.4
LOI, 1000° C	8.4	8.4	25.2	11.7	7.5	10.3	11.1	12.5

Compound	Montana		Ohio					
	Spring Creek Coal		COCC,	COCC corehole JMB 26-20				
	8433	8434	8445	8440	8441	8446	8447	8448
Al_2O_3	13.6	8.31	15.87	13.79	19.46	13.98	19.08	10.01
CaO	4.48	15.81	.25	6.58	.24	4.76	1.68	16.93
Fe_2O_3	3.29	4.15	7.78	4.58	4.58	6.58	8.01	9.58
K_2O	2.05	1.21	2.65	3.13	3.37	2.89	3.49	.17
MgO	2.49	4.97	1.16	4.81	1.82	2.49	2.49	1.66
MnO_2	.43	.13	.02	.02	<.01	.03	.03	.21
Na_2O	1.48	.85	.34	.86	.88	.74	.44	.61
P_2O_5	.08	.12	.06	.07	.06	.07	.09	.79
SiO_2	60.11	43.85	60.11	50.05	59.46	52.41	51.12	35.94
TiO_2	.67	.42	1.05	.67	1.05	.77	.88	.52
LOI, 105° C	3.1	.51	1.8	4.3	2.0	3.2	2.1	2.1
LOI, 1000° C	11.9	20.9	8.2	15.8	8.1	12.0	9.4	15.2

LOI Loss on ignition.

Table A-7.—Chemical analyses of shales received from AML States, percent—Continued

Compound	Ohio									
	COCC corehole JMB 35-20						Corehole 2548		Corehole 2562	
	7982	7983	7989	7991	7995	7996	6630	6631	6282	6624
Al_2O_3	15.68	11.71	17.19	19.27	12.66	18.51	16.06	18.32	1.72	15.87
CaO	6.44	11.47	.29	1.18	12.59	.83	.83	.35	<.3	.83
Fe_2O_3	5.29	4.43	5.01	6.72	6.15	9.72	15.73	9.15	2.15	5.72
K_2O	3.01	2.65	2.53	3.13	2.77	3.25	3.25	3.37	.13	2.53
MgO	1.99	6.3	1.66	2.32	1.99	2.32	2.32	1.56	.06	2.16
MnO_2	.06	.06	.06	.06	.08	.03	.3	.36	<.01	.08
Na_2O	.97	.73	.88	.73	.71	.5	.46	.44	<.05	2.16
P_2O_5	.58	.09	.04	.07	.12	.09	.07	.05	.02	.08
SiO_2	51.34	43.21	60.75	57.33	46.63	54.97	46.63	49.84	3.64	63.74
TiO_2	.8	.62	1.05	.97	.93	.67	.98	.98	<.2	1.17
LOI, 105° C ...	2.8	2.9	.86	1.6	2.2	2.7	.35	.51	1.2	.48
LOI, 1000° C ..	11.6	18.9	10.2	8.4	15.3	8.7	12.0	14.2	91.1	5.3

Compound	Ohio							Pennsylvania: Anthracite hole 28	
	Corehole 2567		Corehole 2599		Corehole 2617				
	6622	6623	6627	6634	6632	6633	7347	7155	7157
Al_2O_3	17.19	21.91	19.46	14.55	21.91	20.59	21.35	30.22	19.83
CaO	.99	.56	.55	2.38	.39	.08	.55	.14	.2
Fe_2O_3	7.86	5.43	6.72	5.43	6.29	3.72	5.86	2.15	6.58
K_2O	3.25	3.49	3.86	2.89	4.1	3.62	3.86	4.58	3.49
MgO	2.16	1.13	1.99	1.28	1.99	1.34	1.58	12.6	1.41
MnO_2	.14	.05	.09	.11	.08	.02	.08	.03	.14
Na_2O	.94	.49	.75	.53	.42	.4	.35	.42	.32
P_2O_5	.08	.13	.07	.1	.08	.04	.09	.02	.04
SiO_2	55.83	55.4	56.04	53.05	54.54	60.53	54.33	49.62	58.82
TiO_2	1.08	1.0	1.0	.95	.93	1.22	.98	1.18	1.1
LOI, 105° C ...	.55	.81	.39	1.0	.58	.58	.45	.74	.4
LOI, 1,000° C ..	9.5	8.9	7.6	16.5	8.3	6.5	9.4	19.7	8.2

Compound	Pennsylvania									
	Eastern hole 7A			Eastern hole 17			Western hole 1		Western hole 7	
	8360	8361	8362	6274	6275	7165	8318	8319	6278	6280
Al_2O_3	20.21	15.68	20.02	21.35	20.97	17.0	19.08	17.76	17.19	19.08
CaO	.83	1.29	.35	.56	.15	.53	2.24	.91	1.54	.46
Fe_2O_3	3.72	6.86	7.44	7.15	2.15	8.15	8.01	10.15	8.58	8.44
K_2O	3.74	2.65	3.13	3.98	3.01	2.77	3.25	3.01	2.89	3.13
MgO	1.66	1.82	1.66	1.66	.9	1.39	1.99	1.99	1.99	1.82
MnO_2	.06	.09	.16	.09	.03	.19	.08	.09	.19	.19
Na_2O	.23	.13	.26	.22	.18	.2	.22	.19	1.05	.62
P_2O_5	.03	.11	.05	.08	.03	.08	.38	.05	.03	.06
SiO_2	61.39	62.67	52.62	54.33	65.45	57.11	53.26	54.54	57.54	52.41
TiO_2	.88	1.07	.88	1.02	1.35	.95	1.18	1.17	1.08	1.08
LOI, 105° C ...	.52	.48	.7	.43	.41	.41	.75	.56	.28	.21
LOI, 1,000° C ..	6.4	7.6	10.7	8.9	9.2	9.2	9.3	10.0	7.5	10.9

LOI Loss on ignition.

Table A-7.—Chemical analyses of shales received from AML States, percent—Continued

Compound	Pennsylvania								West Virginia:
	Western hole 24						Western hole C8		Hole 191-71,
	8322	8325	8326	8327	8328	8329	7352	7353	8309
Al_2O_3	20.02	8.88	20.21	14.55	17.0	16.06	21.53	18.13	20.59
CaO	.48	14.69	.41	.36	.43	.95	<.025	<.025	.43
Fe_2O_3	7.87	3.0	9.01	7.72	7.15	10.3	4.43	4.86	7.15
K_2O	4.58	2.77	3.62	2.77	2.77	2.65	3.49	3.01	3.13
MgO	3.32	10.45	1.82	2.16	1.62	2.12	1.82	1.43	2.16
MnO_2	.05	.06	.25	.03	.16	.23	.03	.08	.06
Na_2O	.44	.47	.54	.55	.8	.48	.42	.38	.63
P_2O_5	.07	.08	.06	.06	.06	.09	.04	.05	.06
SiO_2	53.26	31.66	54.12	58.82	55.4	34.65	56.26	55.4	56.26
TiO_2	.12	.38	.98	.92	1.03	.6	1.07	.93	1.02
LOI, 105° C ...	1.7	1.0	.41	.65	.51	.9	.77	.61	.95
LOI, 1,000° C ..	7.8	24.7	6.2	10.7	10.1	30.7	7.3	12.2	8.3

LOI Loss on ignition.

Table A-8.—Chemical analyses of siltstones received from AML States, percent

Compound	Colorado: Picketwire Valley, 7779	Kentucky: Great Western Coal 6982	6983	6985	7344	8154	8155	8157	Montana: Decker Coal, 8431
Al_2O_3	12.66	13.98	15.87	6.61	19.08	12.66	21.72	11.15	10.96
CaO	.41	.63	1.13	20.43	.83	2.8	.77	.59	4.9
Fe_2O_3	7.44	8.15	6.86	3.29	6.15	5.86	6.58	8.58	3.15
K_2O	1.69	2.53	3.01	1.12	3.74	.19	4.22	2.05	2.41
MgO	1.36	1.99	2.16	4.48	2.32	1.82	2.49	1.41	2.82
MnO_2	.13	.16	.13	.11	.11	.13	.09	.21	.06
Na_2O	1.35	1.35	1.31	1.04	1.33	1.62	1.02	.74	.82
P_2O_5	.05	.07	.07	.12	.05	.08	.06	.07	.07
SiO_2	65.03	64.81	59.68	40.64	55.19	65.45	54.76	61.82	61.6
TiO_2	.58	1.1	1.03	.52	1.12	.83	.93	.88	.52
LOI, 105° C	.87	.27	.28	.41	.27	.31	.93	.47	.59
LOI, 1,000° C	5.1	7.0	6.9	22.7	8.5	7.1	7.8	9.3	10.4

Compound	Ohio: Corehole 2562, 6626	Pennsylvania: Anthracite hole CH-1, 7159	Pennsylvania: Eastern hole 17, 6273
Al_2O_3	13.98	17.19	14.73
CaO	.1	<.1	.63
Fe_2O_3	2.72	3.86	3.43
K_2O	2.65	2.65	2.41
MgO	.93	.93	1.59
MnO_2	.03	.05	.05
Na_2O	.31	.54	.09
P_2O_5	.04	.02	.04
SiO_2	73.58	69.09	68.66
TiO_2	1.25	1.15	1.0
LOI, 105° C	.24	.48	.25
LOI, 1,000° C	4.0	4.4	4.7

LOI Loss on ignition.

Table A-9.—Chemical analyses of other rocks received from AML States, percent

Compound	BASALT Colorado: Coal Bank Canyon 7775	BASALT Colorado: Coal Bank Canyon 7776	CONGLOMERATE Ohio: Corehole 2567, 6285	CONGLOMERATE Pennsylvania: Anthracite hole CH-1 7354	CONGLOMERATE Pennsylvania: Anthracite hole CH-1 8357	GRAYWACKE Colorado: Picketwire Valley, 7780	SLATE Illinois: Midland Coal, 6976
Al_2O_3	17.0	13.79	0.68	3.4	4.16	13.6	11.9
CaO	2.1	9.93	.07	<.025	.07	.59	2.38
Fe_2O_3	4.43	9.72	1.43	1.86	.61	5.15	3.86
K_2O	.95	1.93	<.05	.43	.53	1.57	2.65
MgO	1.26	6.96	.12	.1	.13	1.23	2.32
MnO_2	.03	.19	<.01	.06	<.01	.05	.06
Na_2O	3.37	2.97	<.05	.07	.12	1.75	.34
P_2O_5	.05	.3	.02	.02	.03	.06	ND
SiO_2	63.74	45.13	96.68	88.55	91.98	68.66	32.3
TiO_2	.68	1.83	<.2	<.25	.33	.68	.47
LOI, 105° C	1.2	1.4	<.1	.24	.11	.95	.37
LOI, 1,000° C	4.2	4.3	.56	1.9	1.3	4.9	42.0

Compound	SURFACE SOIL Montana: Westmoreland Resources Gray rock, 8364	SURFACE SOIL Montana: Westmoreland Resources Brown rock, 8365
Al_2O_3	9.82	8.69
CaO	4.62	6.02
Fe_2O_3	5.58	2.57
K_2O	2.05	1.93
MgO	3.32	2.82
MnO_2	.05	.08
Na_2O	.42	.88
P_2O_5	.06	.06
SiO_2	59.25	66.95
TiO_2	.47	.43
LOI, 105° C	1.3	1.4
LOI, 1,000° C	13.0	9.9

LOI Loss on ignition.
ND Not determined.

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